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FUEL BEETS: A PROSPECTIVE ENERGY CROP FOR MONTANA

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FUEL BEETS: A PROSPECTIVE
ENERGY CROP FOR MONTANA

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ABSTRACT

Yield and biomass characteristics have been investigated for seven beet cultivars grown in southcentral Montana during the 1982 season. Root biomass made up in excess of 80% of the total dry matter, and gave fresh weight yields ranging from 34.6 to 65.8 tons per acre. The productivity of two high-yielding cultivars, Meka Otofte and Krake, compared favorably with yield data from trials conducted elsewhere in the United States.

Root biomass comprised 60% to 77% non-reducing sugar (sucrose) on a dry weight basis. Fuel beets contained a three to eightfold greater mass of fermentable carbohydrates, a three to tenfold greater energy yield from fermentable carbohydrates and a higher percentage of total biomass energy apportioned to fermentable carbohydrates than barley, wheat or corn grown in Montana.

Estimated ethanol yield from the fermentable carbohydrates of fuel beets ranged from 528 to 928 gallons per acre. The highest potential ethanol yields (in excess of 900 gallons per acre) surpassed high sucrose sugar beet cultivars by as much as 200 gallons per acre, barley and wheat by 800 gallons per acre, and corn by 700 gallons per acre.

Oils, polyphenols, crude fiber and lignin were considered separately as minor constituents of fuel beet biomass because of low yields. Collectively, however, these residual materials remain after sugar extraction from whole plant biomass, and they make up 35% to 45% of the total biomass energy at harvest.

It is concluded that beet cultivars screened for high yield of fermentable carbohydrates could be grown successfully in Montana to produce sufficient raw material for a regional fuel alcohol industry.

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INTRODUCTION

Beta vulgaris is a genetically diverse species containing numerous cultivars exploited for a wide variety of uses. A systematic identification of the cultivars is difficult since the identification of any one is often based on end use rather than genetic traits. The cultivars of B. vulgaris of interest in this study may be broadly classified as red beets, sugar beets, mangels, fodder beets and fuel beets.

Red beets are those valued as a vegetable for human consumption and they are harvested before attaining maximum root weight.

Sugar beets are grown for commercial sugar (sucrose) production. Sugar beet cultivars characteristically have relatively large underground taproots (1-3kg fresh weight) containing 14-18% sucrose on a fresh weight basis.

Mangels are cultivars of B. vulgaris grown in Europe as forage for livestock. These beets are characterized by their very large taproots (3-6kg fresh weight), low sugar content (4-10%) and substantial taproot growth above the surface of the soil.

A fodder beet is any cultivar of B. vulgaris used as livestock feed, but it has generally been synonymous with mangel.

The term "fuel beet" has been coined recently to denote any cultivar of B. vulgaris with potential as feedstock for fuel alcohol production (Theurer et al 1981). In this report, "fuel beet" will be used in reference to all cultivars being investigated.

Total dry matter production is greater in beets than wheat, barley or potatoes grown in the same climate (Odum 1959; Holliday 1966). In

Holland, for example, total dry matter yields expressed as tons per acre per year was 6.45 for beets, 5.50 for wheat and 3.70 for potatoes (Odum 1959). In England, comparative yield data expressed as above were 4.86 for wheat, 4.44 for barley, and 6.75 for sugar beets (Holliday 1966).

Sugar beets grown in Montana produce a considerably greater yield of fermentable carbohydrate than cereal grains. Calculations based on data derived from Agricultural Statistics (USDA, 1980) indicate the following fermentable carbohydrate yields expressed as pounds per acre: beet, 6336 (assuming 16% sugar); corn, 3353; wheat, 1097; barley, 944.

Energy index is the amount of fermentable sugar or starch expressed as the percent of total biomass on a dry weight basis (Doney 1981A). This value has been used as a measure of the utility of a species as a source of feedstock for fuel alcohol production. Characteristic energy indices are as follows: corn, 35%; potatoes, 45%, and sugar beet, 50% (Doney 1981A). Beets have a relatively high energy index because a large percentage of the photosynthetically fixed carbon is stored as sucrose in the tap root during the first growing season rather than being utilized for vegetative/reproductive growth. Among beet cultivars, fodder beets divert more photosynthate to sugar than sugar beets (Doney 1981A). Although fodder beets have a lower percent sugar than sugar beets, they produce a greater quantity of sugar per plant because of their large taproots. Consequently, fodder beets may have a slightly higher energy index than sugar beets.

Fuel beets have been given serious consideration as a renewable energy source because of their high content of fermentable sugars, particularly sucrose. In sugar beets, 40 to 50% of the total plant biomass is stored as sucrose in a large taproot during the first year of growth (Doney 1980A). Fermentable sugar yields of 3.89 to 6.88 tons per acre have been reported in field trials conducted at Logan, Utah and Aberdeen, Idaho (Theurer et al 1981). Sugar beet x fodder beet hybrids tested in these trials appeared to have the best potential for fuel alcohol production. The range of potential alcohol yield for 35 cultivars tested in the Logan and Aberdeen trials was 558 to 1022 gallons per acre, with a mean for all cultivars of 761 gallons per acre.

Regional differences in sugar yield and thus potential alcohol production are evident. Despite comparable sugar contents, beet cultivars grown at Aberdeen, Idaho had higher potential alcohol yields than identical cultivars grown at Logan, Utah. At Huntley, Montana, sucrose yields ranged from 2.56 to 3.60 tons per acre for Great Western Monohybrid D2 (GWD2) a sugar beet hybrid (Haby et al 1981), whereas the same cultivar had a yield of 4.85 tons per acre at Logan, Utah and 5.92 tons per acre at Aberdeen, Idaho (Theurer et al 1981).

Apart from regional differences, a lower root yield reported for GWD2 could be attributed to the loss of a portion of the root crown because of "topping," i.e., the conventional practice of removing leaves and a portion of the exposed part of the beet root prior to harvest. In fuel beet harvests, the entire crown is left intact since only leaves are removed from the root. Consequently, yield data for sugar beets are not exactly comparable to yield data for fuel beets. Nevertheless, regional differences in yield are well established (Theurer et al 1981).

Estimates of alcohol production from fuel beets have been based on conversion factors (20.3 gallons ethanol per ton of beets; 14 lbs sugar per gallon of ethanol) and conversion efficiencies ranging from 84 to 90% (Anon 1980; Theurer et al 1981). As noted earlier potential ethanol yields ranging from 558 to 1022 gallons per acre could be achieved depending on the cultivar and locality. Beet alcohol yield data compare favorably with similarly derived estimates for conventional crops which give the following alcohol yields per acre: corn, 283 gallons; wheat, 82 gallons; and potatoes, 316 gallons (Doney 1980).

Fermentative ethanol production has been investigated for whole beets (Ware 1880), sugar beet molasses (Surface 1910), and fodder beets (Kosaric 1983). The recent investigation by Kosaric (1983) is particularly relevant. Fermentations carried out with different yeast strains gave ethanol production rates from 2.3 to 3.9 grams ethanol per liter per hour, with a conversion coefficient of 0.46 to 0.51 grams ethanol produced per gram sugar utilized. These and other kinetic parameters were determined using a batch fermenter and they indicated that fodder beets could produce 640 gallons of ethanol per acre. By-products of the fermentation included 268kg yeast biomass and 2125kg pulp per acre of beet root biomass. Therefore, in addition to ethanol, one acre of fermented beet root biomass would produce significant amount of yeast and pulp as major by-products. Carbon dioxide would also be a major by-product of the anaerobic conversion of glucose to ethanol since 916kg CO_2 would be produced with a fermentation conversion efficiency of 50%.

A consideration of the energy requirements for alcohol production from fuel beets indicated that beet ethanol would probably have a zero energy balance, i.e., the amount of energy in the product (ethanol) would equal the energy needed to produce it (Doney and Theurer 1980). Estimates of the energy input to produce one gallon of ethanol from beets included 32,448 BTU to grow the crop; 25,217 BTU to prepare clear juice for fermentation, and an unknown amount of energy for fermentation, distillation, and marketing aspects of production. Since ethanol contains 84,425 BTU per gallon, these latter energy costs could not exceed, collectively, 26,760 BTU without incurring a negative energy balance. It is noteworthy that the energy in residue (leaves and pulp) and yeast biomass was not included in arriving at the energy balance for alcohol production from beets.

Doney and Theurer (1980) suggested several modifications to give a favorable energy balance for alcohol production from fuel beets. These included increased crop productivity, reduced conversion costs related to juice extraction and fermentation, integration of beets with other crops and utilization of low priority energy sources such as geothermal to produce high energy fuel.

The objective of this study was to evaluate the productivity of selected beet cultivars in relation to their potential as a renewable energy crop. Six cultivars grown in southcentral Montana have been evaluated for total biomass yield and the component yields of shoot and root biomass. Yield was further characterized on the basis of several classes of chemical constituents which included sugars, oils, polyphenols, starch, lignin, crude fiber and residual biomass. Energy content was determined for root biomass, shoot biomass and the chemical constituents of each. The calorimetric values obtained allowed an assessment of energy partitioning in each cultivar and a comparative evaluation of net energy yield in each beet cultivar with other crops grown in Montana.

MATERIALS AND METHODS

Seven cultivars of *Beta vulgaris* were grown at the Southern Research Center of the Montana Agricultural Experiment Station at Huntley, Montana in 1982. As indicated in Table 1, these cultivars consisted of one sugar x sugar hybrid, three sugar x fodder hybrids, and three fodder x fodder hybrids. Seed was provided by Dr. Devon Doney and Dr. Claire Theurer at the Sugar Beet Research Unit of the USDA at Logan, Utah.

The fuel beet trial consisted of four row plots with the cultivars arranged in a randomized block design utilizing six replications for each cultivar. Beets were planted on April 30, 1982, and harvested October 16-30 (growing season of 168-182 days). The plots were planted in thirty-five foot rows with a twenty-two inch spacing between rows. They were shortened to thirty feet one month after emergence and each row was then hand-thinned to give an eight inch spacing between beets. The trial received 60 lbs of nitrogen before planting.

Harvest - Entire beets were harvested by hand. Leaf biomass was trimmed from root biomass, but unlike conventional topping of sugar beet cultivars, the crown of the root biomass was not removed with the leaves. Shoot and root fresh-weights were determined gravimetrically in the field. Samples of root and shoot biomass were then brought to Eastern Montana College and dried at 55C for dry-weight determinations.

Chemical Analyses - Sugars - Sucrose content of root biomass was determined polarimetrically on 12 replicates of each cultivar by the Great Western Research Center in Longmont, Colorado. Alternatively, dried root or shoot biomass samples were assayed for reducing and non-reducing sugars at Eastern Montana College as follows. Comminuted biomass samples (0.5g) were extracted with 80% ethanol for 24 hr at room temperature. After ethanol removal, insoluble residue in the aqueous samples was removed by centrifugation at 500g for 10 min. The supernatant was then decanted and further clarified with neutral lead acetate (AOAC 3.105a in Horwitz 1980). Excess lead was removed by adding solid sodium oxalate crystals until no further cloudiness due to lead oxalate was apparent. Aliquots of this solution were assayed for reducing sugars by the Somogyi titrimetric method (AOAC 3.120 in Horwitz 1980). To assay for non-reducing sugars, aliquots were first inverted with 3N HCl for 48 hr at room temperature, then neutralized with 2N sodium carbonate. Neutral, inverted solutions were assayed for reducing equivalents as in AOAC 3.120 above. Non-reducing sugar content was the difference in reducing strength expressed in glucose equivalents determined before and after inversion.

Starch - Starch determinations were made using a modified procedure derived from AOAC 3.120 (Horwitz 1980). Samples of dried biomass (usually 0.5g) were boiled in a small volume of water to gelatinize the starch, after which the starch was solubilized in 30% perchloric acid. Protein in the samples was removed by precipitation with 1.7% uranyl acetate. Solubilized starch in the protein-free samples was precipitated with an iodine-potassium iodide solution in 3% NaCl. After several washings in alcoholic NaCl, the starch-iodine complex which had formed was decomposed with alcoholic NaOH. The liberated starch was washed several times with alcoholic NaCl and subsequently hydrolyzed in 0.7N HCl in a boiling water bath for 2.5 hr.

The acid solution was neutralized with NaOH and an aliquot was taken for reducing sugars as above. Known standards of soluble potato starch were used to determine starch content in the biomass samples.

Oils, polyphenols, and hydrocarbons - Four to six replicates of comminuted biomass samples, each weighing 15-30g, were sequentially extracted in a Soxhlet apparatus for 24-48 hr using the method of Buchanan et al (1978). Acetone extractives were obtained first and these were partitioned between hexanes to extract oils and 87.5% EtOH to extract polyphenols. The residue remaining after acetone extraction was dried in a 55C oven and later extracted with cyclohexane to obtain a hydrocarbon fraction. Initially, the solvents were removed from oils, polyphenols, and hydrocarbons by evaporation in a Buchi rotary evaporator. The residues were then quantitatively transferred to evaporating dishes and allowed to dry further at 40C. Weights were determined gravimetrically and expressed on both a dry and fresh weight basis.

Lignin - The dried residue remaining after acetone and cyclohexane extraction was used for lignin determinations following a modification of the indirect-method given in AOAC 3.126 (Horwitz 1980). One gram samples were washed sequentially with ethanol and ether, dried, and digested overnight at 40C in 1% pepsin in 0.1N HCl. The residue was filtered, washed, and refluxed for 1 hr in 5% H_2SO_4, then held for 2 hr at 25C in 72% H_2SO_4 and refluxed again for 2 hr in 3% H_2SO_4. The residue remaining after acid digestion was washed and dried at 100C. Lignin content was determined by loss in weight on ignition at 600C.

Crude fiber - Crude fiber content was determined using a modified acid-alkali digestion as given in AOAC 7.068 (Horwitz 1980). One gram samples of oil and hydrocarbon-free residue were sequentially refluxed for 30 min in 1.25% H_2SO_4 and 1.25% NaOH. After a final wash in 1.25% H_2SO_4 and several rinses of boiling water, the residue was dried overnight at 100C. Crude fiber content was determined by loss in weight on ignition at 550C.

Protein - Total nitrogen in biomass was determined by direct Nesslerization of ammonia produced by sulfuric acid and hydrogen peroxide digestion (Dotti and Orten 1971). Nitrogen content was determined calorimetrically and expressed as percent protein using a conversion factor of 6.25 as is used for corn and sorghum (AOAC 14.068 in Horwitz 1980).

Calorimetry - The energy content of whole leaf tissue, extractives and residual biomass was determined with a Parr model 1241 adiabatic oxygen bomb calorimeter. Corrections were made for the heat of formation of nitric acid and heat of combustion of the fuse wire. A thermochemical correction for the heat of formation of sulfuric acid was not included since preliminary analyses indicated that the sulfur content of whole leaf tissues was negligible.

Statistics - Statistical comparisons were made using a modified least significant difference (LSD) procedure or Tukey's Honest Significant Difference procedure for multiple comparisons with an SPSS program on a DECsystem 20/60. All comparisons were made at the 5% level of significance.

RESULTS

Seedling germination/Emergence - Significant differences in seedling germination or emergence were observed among the cultivars tested in this study. Based on a planting density of 1 beet per 8 inches, the optimum number of beets would be 45 per 30 ft. With the exception of Peroba and GW 149, all cultivars had less than 75% of the optimal number of beets present at harvest (Table 1). The percentage of beets harvested was lowest for Mammoth Red (52.9%) and highest for GW 149 (95.1%). The use of either pelleted or bare seed did not appear to be a factor influencing emergence or subsequent survival. It is probable that genetic differences related to seed longevity, viability after germination and temperature optima for germination contributed to the large differences in beet survival. These factors were not investigated in this study.

Calculation of yield - Error attributed to variability in seedling germination or emergence and not directly related to productivity was minimized by calculating mean root weights based on the total root harvest for each cultivar. These data are given in Table 2. Mammoth Red roots had the greatest mean fresh weight of 3.78 lb whereas GW 149 had the lowest mean fresh weight of 1.97 lb.

The mean root fresh weight obtained for each cultivar was used to derive yield estimates based on optimum planting densities as given in Table 3. The "corrected" yield data were then compared to independently obtained yield data derived solely from a consideration of total root weight at harvest. As indicated in Table 3, the corrected yield for GW 149 closely approximated the uncorrected yield since the high germination and seedling survival of this cultivar approached an optimum planting density. In contrast, the uncorrected yield of Mammoth Red did not compare well with the corrected yield since poor germination/seedling survival precluded a biomass yield at harvest that would have been representative of the productivity of this cultivar. Thus the corrected yield data in Table 3 are interpreted as optimum yields. Corrected yields are used as the basis for all subsequent determinations in this report because a better indication of productivity is obtained by eliminating variation in productivity due to differences in germination.

Root yield - Root fresh weight yield ranged from 34.6 tons per acre for GW 149, a sugar x sugar hybrid, to 65.8 tons per acre for Mammoth Red, a fodder x fodder hybrid (Table 3). Monriac, Meka Otofte, and Krake had statistically equivalent yields of 55.8 to 58.0 tons per acre. Monofix and Peroba also had statistically equivalent yields of 45.9 and 43.9 tons per acre, respectively.

The water content of root biomass ranged from 78.8% for GW 149 to 91.2% for Mammoth Red (Table 5). All other cultivars had a root water content between 83.8% and 87.6%. It is evident that water content varied significantly and that water comprised not less than 80% of the fresh weight of root biomass for all cultivars except GW 149.

The data in Table 7 indicate that root dry weight yield was greatest for Meka Otofte (8.5 tons per acre) and least for Peroba (5.4 tons per acre). Least significant difference analysis of the yield data suggested that three statistically equivalent groups were present. The first group contained Peroba and Mammoth Red with a mean yield of 5.6 tons per acre. The second group consisted of Monofix, GW 149 and

Monriac with a mean yield of 7.7 tons per acre. The third and highest yielding group consisted of Meka Otofte and Krake with a mean yield of 8.4 tons per acre. Thus the difference in root yield was 2.8 tons per acre between the high and low yielding cultivars, with the high yield value representing a 54% greater yield than the lowest yield cultivars.

Shoot yield - Shoot biomass for all cultivars consisted of a mass of petiolate leaves attached to the upper portion of the root or crown. Limited sampling of shoot biomass gave a maximum fresh weight yield of 19.6 tons per acre for Krake and a minimum yield of 9.2 tons per acre for Mammoth Red (Table 4). Most cultivars had leaf biomass yields between 11 and 12 tons per acre.

In contrast to root biomass, shoot biomass had little variation (range 88.4% to 91.1%) in water content (Table 6). The mean shoot water content was 89.5% and it did not differ significantly for all cultivars investigated in this study.

The dry weight yield of shoot biomass ranged from 1.0 to 2.1 tons per acre (Table 7). Meka Ofofte and Krake had high, statistically equivalent yields with a mean value of 1.9 tons per acre. All other cultivars had statistically equivalent yields ranging from 1.0 to 1.3 tons per acre.

Leaf biomass gathered at harvest represented a fraction of the total leaf biomass produced during the growing season since dried leaf biomass/litter was evident to varying degrees in all cultivars. For example, large number of senescing or dead leaves were observed on the crown of Mammoth Red, suggesting that only a small amount of the plant's total photosynthetic biomass was present. In contrast, few dead leaves were observed on Krake, suggesting that senescence of photosynthetic biomass was minimal for this cultivar.

Total biomass yield - Table 7 gives the total biomass yield for each cultivar. This value is the sum of root biomass and shoot biomass yield expressed on a dry weight basis. The range of total biomass yield was 10.2 tons per acre (Meka Otofte) to 6.2 tons per acre (Monofix). Mean yield values for all cultivars were 7.24 tons per acre for roots, 1.52 tons per acre for shoots, and 8.76 tons per acre for total biomass.

Total biomass yield was correlated directly with root biomass yield, but not with shoot biomass yield for all cultivars. For example, the high root biomass yields of Krake and Monriac correlated well with their high total yield, but the shoot biomass yield of Krake was nearly double that of Monriac. Meka Otofte and Krake produced the greatest root, shoot, and total biomass yields, whereas Mammoth Red, Peroba and Monofix had the lowest. Monriac and GW 149 were noteworthy exceptions since these cultivars had medium root and total biomass yields but low shoot biomass yields.

The apportionment of biomass between root and shoot is expressed as a percentage of the total biomass at harvest in Table 8. Root biomass had a mean dry matter content for all cultivars of 83.5% with a range of 79.8% (Krake) to 88.0% (Monriac). Shoot biomass had a mean dry matter content of 16.5% with a range of 12.0% (Monriac) to 20.2% (Krake).

Sugar and potential alcohol yield - Root sugar content, yield and potential ethanol yield are given in Table 9. Sucrose content ranged from a low 5.44% for Mammoth Red to a high of 14.99% for GW 149. Meka

Otofte, Monofix, and Krake had similar sucrose contents of approximately 11.1%. Monriac and Meka Otofte also had similar yields with a mean of 10.1%. The sucrose content of Peroba (7.96%) was low compared to all other cultivars except Mammoth Red which had the lowest sucrose content of all cultivars tested.

Reducing sugars were a minor component of the total fermentable carbohydrates (defined as sucrose + reducing sugars) and never exceeded 0.62% of the fresh weight. No relationship was evident between sucrose content and the level of reducing sugars. For example, Mammoth Red and GW 149 had comparable reducing sugar levels, despite a highly significant difference in sucrose content.

Fermentable carbohydrates - The yield of fermentable carbohydrates in Table 9 was calculated from the content of sucrose + reducing sugars multiplied by the root yield. Yields thus obtained ranged from 3.70 to 6.46 tons per acre. Despite sucrose contents less than GW 149, higher fermentable sugar yields were obtained with Krake, Meka Otofte, and Monriac because the higher root yields of the cultivars overcompensated for the lower sucrose content. A direct correlation was evident between root dry matter yield and fermentable sugar production. For example, Krake had the highest fermentable sugar tonnage and a high yield of root dry matter. Conversely, Mammoth Red had the lowest fermentable sugar yield and a low root dry matter yield. It is noteworthy that root fresh weight yield was a misleading measure of fuel beet productivity (cf Tables 4, 7, 9).

Potential alcohol per acre as given in Table 9 was calculated on the basis of 14 lbs sugar per gallon of ethanol (Theurer et al 1981). Alcohol yields thus obtained ranged from 528 to 928 gallons per acre.

The alcohol yield data indicated that statistically equivalent yields were obtained for the cultivars grouped as follows: Meka Otofte and Krake, 917 gallons per acre; Monriac, 814 gallons per acre; Monofix and GW 149, 742 gallons per acre; Mammoth Red and Peroba, 531 gallons per acre. Thus the highest potential alcohol yields in this study were from a SxF and a FxF hybrid while the lowest potential alcohol yields were observed in FxF hybrids.

Biomass apportionment - As given in Tables 10 and 11, shoot and root biomass were subdivided into the following six components: oils, polyphenols, ethanol extractives, crude fiber, lignin and residual biomass.

Shoot biomass characteristically had an oil content (range 3.0% to 4.0%) approximately threefold greater than root oils, with a range for both of 0.6% to 1.9%. With the exception of Peroba, root biomass had a greater oil yield than shoot biomass because of this larger mass yield (Table 11). The highest total oil yield of 471 lbs per acre was observed in Meka Otofte and was equivalent to approximately 1.2 barrels per acre. Shoot biomass oil yields never exceeded 0.6 barrels per acre and they were generally much less.

Polyphenols occurred in higher concentration than oils in both root and shoot biomass (Table 10). The polyphenol content of shoot biomass was either equal to or greater than that of root biomass. Nevertheless, root polyphenol yield was always greater than shoot yield by two to sixfold, due to the much greater mass yield of root biomass. The mean yield of polyphenols for all cultivars was 161 lbs per acre for shoot biomass and 580 lbs per acre for root biomass. The range was quite broad and due principally to variation in mass yield rather than content. Shoot biomass polyphenol yield ranged from 97 to 279 lbs per acre while root polyphenols ranged from 465 to 725 lbs per acre.

Ethanol extractives were the single largest, soluble biomass component for all cultivars with respect to both content and yield (Tables 10, 11). Shoot biomass from all cultivars had a mean yield of 21.4% with a range of 15.1% to 28.7%. Root biomass had a threefold greater content of ethanol extractives, with a mean for all cultivars of 66.7% and a range of 62.0% to 75.5%. Differences among genetically different cultivars were inconsistent, although the single sugar x sugar hybrid in this study (GW 149) had the highest content of ethanol extractives on a percentage basis.

The mean yield of ethanol extractives from shoot biomass was 647 lbs per acre, with a range of 466 to 999 lbs per acre.

The ethanol extractive yield from root biomass was much greater due to both the high percentage of ethanol extractives and the greater mass yield of root biomass. The mean yield of ethanol extractives from root biomass of all cultivars was 10,175 lbs per acre with a range of 7167 to 10,910 lbs per acre. The yield of root ethanol extractives was directly correlated with root dry weight and the total yield of fermentable sugars. Sucrose percentage in roots of B. vulgaris is also correlated with percent dry matter in the root (Doney et al 1981).

Crude fiber and lignin were the two insoluble biomass components examined in this study. Crude fiber comprised 7.3% and lignin 8.7% of the total biomass. The crude fiber content of shoot biomass was two to threefold greater than root biomass. Shoot biomass had a mean crude fiber content of 11.3% while roots had 5.5%. Lignin had a similar pattern of distribution, with a mean lignin content of 13.8% in shoots and 7.3% in roots.

Crude fiber and lignin yield was always greatest for root biomass. The mean for all cultivars was 794 lbs per acre for crude fiber and 1037 lbs per acre for lignin. Shoot biomass had a crude fiber and lignin yield which was approximately one-half that of root biomass, although much variation was evident among cultivars. Total mean yield for all cultivars on a whole plant basis was 1134 lbs per acre for crude fiber and 1494 lbs per acre for lignin.

Energy content - Calorific values were determined for shoot biomass, root biomass, oils, polyphenols, ethanol extractives, and residual shoot and root biomass (Table 12). Mean calorific values for whole plant biomass were 3611 cal per gram for shoots and 3710 cal per gram for roots. Soluble materials had mean energy values as follows: oil, 8760 cal per gram; polyphenols, 4312 cal per gram; ethanol extractives, 3905 cal per gram. The residue remaining after the extraction of these soluble materials had a mean calorific value of 3301 cal per gram for shoot residue and 3623 cal per gram for root residue. Calorific values for individual cultivars and any form of biomass or extractive generally varied less than 5% from the mean value given for all cultivars.

Energy yield - The values for energy yield given in Table 13 represent the total energy contained in shoot or root biomass at harvest. They were calculated from mass yields (Table 7) and calorific values (Table 12). Energy yields thus obtained ranged from 4.0 to 6.0 x 10^6 kcal per acre for shoot biomass and 17.9 to 28.9 x 10^6 kcal per acre for root biomass. Meka Otofte had the highest total energy yield (35.2 x 10^6 kcal per acre) and Peroba had the lowest (21.8 x 10^6 kcal per acre). Root biomass contained 81.7% to 88.9% of the total energy at harvest. Shoot/root ratios in table 13 indicate that the energy yield from root biomass was five to tenfold greater than shoot biomass. The high energy-yielding cultivars, Meka Otofte and Krake, had relatively high shoot/root ratios. However, the possible correlation between high total energy yield and a high shoot/root ratio was inconsistent among cultivars. For example, the cultivar with the lowest energy yield, Peroba, had a shoot/root ratio of 0.22, which was the highest of all cultivars.

Energy apportionment - The energy yield calculated for each cultivar has been apportioned into soluble materials consisting of oils, polyphenols and ethanol extractives, and the insoluble residue remaining after extraction (Table 14).

Oils and polyphenols contain a small percentage of the total energy at harvest. Energy yield from oils ranged from 0.61 to 1.90 x 10^6 kcal per acre, values representing 2.5% to 5.1% of the total biomass energy. Polyphenols contained an additional 1.08 to 1.60 x 10^6 kcal per acre (3.6% to 6.5%).

Ethanol extractives were the largest energy component of apportioned biomass. The range of energy yield of this class of extractives was from 13.72 to 20.87 x 10^6 kcal per acre or 55.7% to 65.6% of the total biomass energy. Monriac, Peroba, and GW 149 had in excess of 60% of the total biomass energy apportioned to ethanol extractives, while the other cultivars had from 55% to 58%. Of these three cultivars, only GW 149 had a comparatively high energy yield for ethanol extractives. Krake and Meka Otofte were the only other cultivars which produced in excess of 20 x 10^6 kcal per acre in ethanol extractives, even though both had approximately 10% less biomass apportioned to ethanol extractives at harvest.

The residue remaining after extraction of oils, polyphenols, and ethanol extractives was subdivided into shoot and root components (Table 14). Shoot residue comprised 2.5 to 4.7 x 10^6 kcal per acre or 8.1% to 13.1% of the biomass energy. Because of its greater mass yield, root residue had approximately a twofold greater energy yield of 4.5 to 8.8 x 10^6 kcal per acre or 15% to 25% of the total biomass energy yield at harvest.

DISCUSSION

Root weight and sucrose content - An inverse relationship between fresh weight and sucrose content in roots of *B. vulgaris* has been noted in the literature (Bergen 1962; Doney et al 1981; Odlemeyer 1975; Powers 1957). Such a relationship was observed in six of the seven cultivars investigated in this study. For example, Mammoth Red produced a very large taproot (mean fresh weight 3.8 lb) having a low sucrose content (5.4%), while GW Monohybrid 149 produced a relatively small taproot (mean fresh weight 2 lbs) having a high sucrose content (15%). Peroba, a FxF hybrid, was a noteworthy exception which had both low root biomass and low sucrose content.

The fuel beet cultivars investigated in this study that appear to hold the most commercial promise as fuel beets are those having a moderate sucrose content (9-12%) and high mass yield in excess of 8 tons dry weight per acre. Monriac, Meka Otofte and Krake may be characterized as moderate sucrose-high root biomass cultivars. Their high root biomass yield compensated for a moderate sucrose content to produce comparatively high yields of fermentable carbohydrate.

The inverse relationship observed between root fresh weight and root sucrose content is interesting because it suggests that photosynthetically fixed carbon is partitioned to forms of root biomass other than sucrose. Alternatively, the observed differences in sucrose content may simply be a function of variation in water content. Data in Table 23 suggest that the percentage allocation of photosynthetically reduced carbon to sucrose in root biomass is not constant for all cultivars. The specific sucrose content given in

Table 23 is defined as the percentage of sucrose in dry biomass. The cultivars investigated in this study had specific sucrose contents ranging from 61.8% to 76.6% of total dry matter in the root. Sucrose has been found to account for up to 70% of the total dry matter in sugar beet roots (Doney et al 1981). It is evident from the data in Table 23 that cultivars such as Krake, Meka Otofte and GW Monohybrid 149 partition a greater amount of photosynthetically fixed carbon in root biomass to sucrose than cultivars such as Mammoth Red, Peroba, Monofix, and Monriac. This suggests that Krake, Meka Otofte and GW Monohybrid 149 are inherently more productive with respect to the apportionment of fixed carbon into a fermentable carbohydrate because a greater percentage of stored dry matter is in the form of sucrose.

Data in Table 5 indicate that significant variation in root water content also occurs among the cultivars in this study, suggesting that differences in root biomass water content contribute to the inverse relationship between root fresh weight and sucrose content. Mammoth Red, for example, had a low sucrose content and a relatively high water content. This is in contrast to GW Monohybrid 149 which had the highest sucrose content and lowest water content of all cultivars. Other cultivars such as Monriac and Peroba had similar water contents but significantly different sucrose contents. Collectively, these data on sucrose content, specific sucrose content and water content in fuel beet roots suggest that variation in sucrose content is a function of both the pattern of carbon apportionment in root biomass and root water content. High root water content is correlated with low sugar and specific sugar content, whereas low root water content is correlated with high sugar and high specific sugar content. Those cultivars having moderate levels of root water (84% to 87%) generally have moderate sucrose levels (8% to 11%). Differences in sucrose content observed in this latter group result solely from variation in specific sucrose content, i.e., the amount of photosynthetically reduced carbon apportioned to storage sucrose in root biomass.

Comparative root sucrose content data from trials conducted in other parts of the Pacific Northwest were available for four of the seven cultivars tested in this study (Table 15). A comparison of the data in Tables 9 and 15 indicates that the sucrose content of all four cultivars (GWD2, Meka Otofte, Krake, and Monofix) grown in Montana was less than values reported in the other trials. The absolute difference ranged from 1.6% for GW Monohybrid 149 to 2.9% for Krake. Expressed as a percentage of the maximum sucrose content, Montana-grown GW Monohybrid 149 had a sucrose content that was 10% less than other trials while Meka Otofte, Krake and Monofix had approximately 20% less sucrose. The preliminary conclusion to be drawn from these data is that fuel beets grown in southcentral Montana would have a sugar content 10% to 20% less than fuel beets grown elsewhere in the Pacific Northwest. However, this comparison is at best tentative because it is based on limited trials conducted over a single growing season and also because annual variation in sugar content is very significant. In the United States from 1970-1978, the raw sugar content for sugar beets varied from a low of 12.9% in 1970 to a high of 13.5% in 1975 (Table 16). This is a 0.6% absolute difference or 4.7% relative difference in raw sugar content. Regional, annual variation in sucrose content is much greater (Table 17). Over a four year period (1979-1982) at the Southern Research Center at Huntley, Montana, the relative difference in the sucrose content of five high-yielding cultivars ranged from 0 to 27.8%. Thus, although fuel beets grown in Montana may have less sucrose than the same cultivars grown elsewhere in the Pacific Northwest, the sucrose content of a fuel beet crop in any given year could be expected to vary annually by as much as 28% due to environmental factors influencing sugar content.

Reducing sugars - The low reducing sugar content of all cultivars investigated in this study is characteristic of beet roots (Theurer et al 1981). Since reducing sugars rarely exceeded 0.5% of the root fresh weight, they are not a significant biomass component in fuel beets.

Fermentable sugars - Photosynthate partitioned to fermentable sugars is 40% to 50% for sugar beets, 25% to 30% for sweet sorghum and 30% to 35% for sugar cane (Doney 1980). The cultivars investigated in this study had a somewhat higher percentage (54% to 63%) of the total plant biomass consisting of fermentable carbohydrates. This result is consistent with the conclusion that fuel beets have a higher percentage of biomass allocated to fermentable sugars than other crops (Doney 1980).

Shoot biomass - As is characteristic of biennials at the end of the first year of growth, most of the reduced carbon in the fuel beet cultivars was apportioned to root biomass. Shoot or leaf biomass harvested at the end of the growing season consisted of 12% to 20% of the total dry weight or 11% to 18% of the total biomass energy at harvest. Nathan (1978) estimated that 1 metric ton of tops is associated with each 1.1 metric tons of roots. Based on dry weights associated with root and leaf biomass (see Table 26), the shoot biomass (i.e., tops) would make up 40% of the total dry matter. Estimates of shoot biomass by Hills et al (1955 and see Nathan 1978) indicated that sugarbeet tops made up approximately 70% of the total dry matter (root and tops). Shoot dry matter yields in the present investigation did not exceed 20% of the total dry matter at harvest. Additional leaf biomass in the form of dead/decaying litter was evident for all cultivars, but harvesting such biomass would be impractical. It is evident that not more than 20% of the total dry matter obtained from living biomass at harvest would be in the form of potentially useful raw materials derived from beet tops.

The utility of shoot biomass as a feedstock would have to be weighed against harvest and production costs. Using shoot biomass as a source of oils, polyphenols, ethanol extractives, crude fiber or lignin does not appear to be economically attractive due to the low yield of these components from shoot biomass.

Shoot biomass could simply be left in the field or serve as a source of feed that could be grazed by livestock after root biomass had been harvested. Both are common practices employed by farmers in sugar beet producing areas. Alternatively, it is conceivable that shoot biomass could be harvested with root biomass and used together as a single source of fermentable sugars for fuel alcohol production. Production cost savings related to topping beets prior to harvest would have to be weighed against increased bulk, transportation, and processing costs associated with shoot biomass.

Root biomass - Root biomass is the single most important component of fuel beet biomass since it represents as much as 88% of the total plant biomass energy at harvest. In contrast to ethanol extractives comprising 66.6% of the total dry root biomass yield, other root biomass constituents such as oils, polyphenols, crude fiber and lignin were comparatively negligible biomass components. Consequently, it is unlikely that these materials could enhance the economic attractiveness of fuel beets in a multiple use application of raw plant biomass. The very high percentage of ethanol extractives (sugars) argues in favor of applications where the use of this fraction is heavily emphasized.

Biomass and energy yield - Biomass and energy yield data for several Montana crops are given in Table 21. Listed in the table are five high yielding sugar beet cultivars and three cereal grains (barley, wheat, and corn). The energy values represent gross energy yields at harvest, i.e., energy inputs for crop production are not represented.

Based on a consideration of biomass yield alone, sugar beets (Table 21) and fuel beets (Table 7) are the most productive crops in Montana. Sugar beet crop yields of 7 tons per acre (dry weight) exceed barley, wheat, and corn by 300% to 800%. Similarly, the yield of fermentable carbohydrates from sugar beets exceed cereal grains by 300% to 1000%.

About 60% of the total biomass of beets is apportioned to fermentable carbohydrates. This compares favorably with other Montana crops. In barley and wheat, 20% of the reduced carbon is apportioned to fermentable carbohydrates while in corn this value is 33%.

Energy yield data in Table 21 parallel mass yield. Of the crops listed in Tables 13 and 21, fuel beets and sugar beets have the greatest energy yield of all crop plants in Montana. The total energy yield at harvest (30 to 35 x 10^6 kcal per acre) probably represents an upper limit of harvestable solar energy for existing cultivars in

Montana since such yields are achieved through conventional but intensive agronomic practices on fertile land. Total energy yields of the cereal grains in Table 21 were 45% to 70% less than beets. Expressed as a percentage of the energy yield of sugar beets (30 x 10^6 kcal per acre), the total biomass energy at harvest is 31% for wheat, 44% for barley and 54% for corn.

The percentage of energy contained in fermentable carbohydrates relative to total biomass was greatest for fuel/sugar beets. In the high-yielding sugar beet cultivars in Table 21, from 62% to 66% of the total biomass energy was in the form of fermentable carbohydrates. In contrast, corn had 33% of the total biomass at harvest in the form of fermentable carbohydrates; wheat, 19%; and barley, 17% to 25%. Expressed as a percentage of that in beets, the fermentable carbohydrate energy yield in cereal grains was 14% for barley, 9% for wheat and 28% for corn.

In summary, fuel/sugar beets contain a three to eightfold greater mass yield of fermentable carbohydrates, a three to tenfold greater energy yield from fermentable carbohydrates and a higher percentage of total biomass energy apportioned to fermentable carbohydrates than barley, wheat, and corn grown in Montana.

Among the seven beet cultivars investigated in this study, two (Peroba and Mammoth Red) had low total energy and fermentable carbohydrate yields compared to the top performing sugar beet cultivars in Table 21. Consequently, these cultivars would be economically unattractive for fuel alcohol production.

Three cultivars (Monofix, GW Monohybrid 149 and Monriac) had fermentable carbohydrate and energy yields that exceeded the best sugar beet cultivars by 15% to 20%. A high yield of fermentable carbohydrates was achieved by the greater root biomass of these cultivars rather than high sugar content. When compared to sugar beets, the sugar content of Meka Otofte (10.8%) and Krake (11.4%) is low enough to make them economically unattractive to the sugar beet industry. However, the high yield per acre of fermentable carbohydrates achieved from high root biomass production suggests that both cultivars would outcompete the best sugar beet cultivars and cereal grains as crops grown for fuel alcohol production.

Potential alcohol yield - The sources of information used to arrive at potential alcohol yields from crops with a high percentage of fermentable carbohydrates were obtained from 1) fuel beet trials conducted in the northwest but outside Montana (Table 15), 2) sugar beet trials of high-performance cultivars grown at the Southern Research Center at Huntley, Montana (Table 24), and 3) agricultural statistics for wheat, barley, and corn yields in Montana or statistical data of a more general nature (Tables 18 and 24).

The data in Table 15 indicate that potential alcohol yields from fuel beet cultivars range from 600-1000 gallons per acre. Comparisons of alcohol yields in this and other studies suggest that general trends are similar, but absolute yields may vary considerably.

Two of the three FxF hybrids in this study (Mammoth Red and Peroba) were low potential alcohol producers. This finding is generally consistent with other trials (cf Tables 9 and 15), but the actual potential alcohol yields of these cultivars was 13% to 30% poorer in Montana. Meka Otofte, another FxF hybrid, was a noteworthy exception since it gave one of the highest potential alcohol yields of all cultivars tested. Its potential alcohol production of 910 gallons per acre was about 25% greater than yields determined in trials outside Montana (Table 15).

All SxF hybrids (Monofix, Monriac, and Krake) gave potential alcohol yields greater than or equal to those reported elsewhere (cf Tables 9 and 15). Krake was an outstanding cultivar with a potential alcohol production of 928 gallons per acre.

These comparisons suggest that fuel beet cultivars with a low potential for alcohol production elsewhere in the United States would perform very poorly in Montana. Conversely, they also suggest that cultivars demonstrating a high potential for alcohol production would perform as well or better in Montana than elsewhere in the Pacific Northwest.

The potential alcohol yields given in Table 17 were calculated for the top performing sugar beet cultivars grown at the Southern Research Center at Huntley, Montana. If an additional 10% potential fuel alcohol is added to these values for the topped beet crown and inducing sugar content, then maximum alcohol yields of 700-800 gallons per acre could be achieved with conventional sugar beets. Since the two top performers in this fuel beet study were not sugar beets, (Krake = SxF hybrid and Meka Otofte = FxF hybrid) it would appear that the proper selection of fuel beet cultivars should not necessarily be based on the pool of sugar beet cultivars commonly grown to evaluate recoverable sucrose yield. The parameter of fundamental importance to fuel beet trials must be total fermentable sugar, not recoverable sucrose yield.

Fodder beets have recently been used as a source of raw juice for ethanol production (Table 26). Fermentations using yeast strains with high conversion yields (conversion yield = amount of ethanol produced expressed as percentage of the theoretical maximum yield) gave a projected ethanol yield of 638 gallons per 4.7 tons of sugar. Expressed fodder beet juice did not require additional nitrogen or phosphorus for fermentation to alcohol. Saccharomyces diasticus 62 was the most promising yeast strain. Its desirable features included 1) a very high conversion yield, 2) high productivity of ethanol, 3) high specific growth rate, and 4) tolerance to high ethanol concentration (Kosaric et al 1983). The high ethanol yield coefficient determined for Saccharomyces diasticus 62 (0.5g ethanol produced per 1g sugar utilized in fermentation) indicates that an ethanol yield of 1 gallon per 15 lbs sugar utilized could be obtained using existing yeast strains and technology. The attractiveness of fuel beets as a source of raw feedstock for fuel alcohol production is suggested by data in Table 18. As calculated by Doney (1980) sugar beets have a potential fuel alcohol yield which is 1.5x greater than potatoes, 1.7x greater than corn, and 6x greater than wheat.

Somewhat more regional data restricted to cereal grains grown in Montana are given in Table 24. Potential fuel alcohol production from barley and wheat would not exceed 100 gallons per acre while corn alcohol production would be approximately 213 gallons per acre. Since high yielding fuel beet cultivars could produce in excess of 900 gallons per acre, the potential production values indicate that fuel beets would produce five to tenfold greater alcohol yields per acre than major cereal grains grown in Montana.

Between 1975 and 1979, inclusive, an average of 1.3 million acres of land was used for sugar beet production in Montana (USDA

Agricultural Statistics 1980). Ten percent of this land (130,000 acres) would produce enough fermentable carbohydrate from high yielding fuel beet cultivars to produce in excess of 100 million gallons (2.4 million barrels) of ethanol. A regional fuel alcohol industry could be established using fuel beets as a source of raw material for ethanol production if the economics of processing beets to alcohol are favorable.

Cost of alcohol from beets - Doney (1980) estimated the adjusted cost of ethanol from sugar beets to be about $1.38 per gallon (Table 25). About 63% ($1.03) of the total cost would be due to the production of the beet crop. The remaining 37% would be for extraction and conversion of beet sugar to ethanol. A credit for residual beet pulp and stillage was also included since these by-products could be sold as a livestock feed. The value of the by-products could be enhanced through cellulose degradation and microbial protein enrichment using Trichoderma neesei, a cellulolytic fungus (Illanes and Schaffeld 1983). The use of low priority fuels (coal, geothermal, solar) would also further reduce reliance on fossil fuels and possibly alcohol production costs as well.

CONCLUSIONS

The primary objective of this project was to evaluate the productivity of several prospective fuel beet cultivars grown in southcentral Montana. Yield data indicate that certain cultivars (Krake or Meka Otofte) selected for a high yield of fermentable carbohydrates would have a lower sugar content but a greater yield of dry matter. These cultivars would produce a total yield of fermentable sugars equal to or greater than the productivity of the same cultivars grown elsewhere in the United States.

Shoot biomass represents 11% to 18% of the total biomass energy at harvest, but the use of this biomass would appear to be limited due to low yields of its constituent oils, polyphenols, crude fiber and lignin. Similarly, the residual pulp remaining after extraction of sugars from root biomass represents 20% to 30% of the total biomass energy at harvest, but does not contain a large yield of oils, polyphenols, crude fiber and lignin. Feeding these materials to livestock appears to be the most attractive end use at this time.

Fuel beet cultivars such as Meka Otofte and Krake produce high yields of fermentable carbohydrates. These cultivars have mass and energy yields of fermentable carbohydrates that are 3 to 10 times greater than barley, wheat and corn grown in Montana. Although the cost of production is one important factor not considered here, it is clear that high-yielding fuel beet cultivars would produce up to 10 times more fermentable carbohydrates per acre than cereal grains in Montana.

Estimated alcohol yield data further indicate that high-yielding fuel beets have the potential to produce 10% to 30% more alcohol per acre than high quality conventional sugar beets. Fuel beets have a lower percentage of sucrose than sugar beets, but their high yield of root dry matter per acre produces a greater yield of fermentable carbohydrates per acre. As suggested by the data of Kosaric et al (1983), factors such as high purity and high sucrose content (important to the sugar beet industry) are not critical for the fermentation of sucrose to ethanol.

Growing fuel beet cultivars capable of producing 900+ gallons of alcohol per acre on 10% of the land presently used in Montana for sugar beet production could sustain a fuel alcohol industry with an annual production capacity in excess of 100 million gallons.

TABLE 1: BEETS HARVESTED BASED ON SEEDLING EMERGENCE/SURVIVAL

Cultivar	Type[1]	Seed[2]	# of Beets[3] ± $s_{\bar{y}}$	Percent at Harvest[4]
GW Monohybrid 149	SxS	Bare-S	42.8 ± 1.84	95.1
Peroba	FxF	Bare-M	42.0 ± 1.16	93.3
Monofix	SxF	Bare-M	32.5 ± 0.96	72.2
Monriac	SxF	Bare-M	30.0 ± 0.94	66.7
Meka Otofte	FxF	Pellet	27.8 ± 1.06	61.8
Krake	SxF	Pellet	25.5 ± 0.81	56.7
Mammoth Red	FxF	Bare-M	23.8 ± 0.87	52.9

LSD 0.05 = 3.2

[1] F = Fodder (Mangel)
S = Sugar

[2] S = Single germ
M = Multiple germ

[3] Harvested per 30' row
$s_{\bar{y}}$ = Standard error of the mean where n=24 for all cultivars

[4] Based on an optimum yield of 45 beets per 30' row

TABLE 2: ROOT YIELD PER BEET

Cultivar	Fresh Weight[1] Lbs. ± $s_{\bar{y}}$	Standard Deviation	Range
Mammoth Red	3.78 ± 0.11	0.52	2.84-4.83
Monriac	3.34 ± 0.10	0.48	2.27-4.34
Meka Otofte	3.24 ± 0.09	0.42	2.56-4.21
Krake	3.21 ± 0.13	0.64	1.54-4.28
Monofix	2.64 ± 0.08	0.40	1.92-3.40
Peroba	2.58 ± 0.06	0.32	1.63-3.13
GW Monohybrid 149	1.97 ± 0.08	0.38	0.99-2.78

LSD 0.05 = 0.41

[1] n=24 (All beets in each of six 30' rows were weighed and counted.)

TABLE 3: ROOT FRESH WEIGHT YIELD

Cultivar	Yield (tons/acre) **Uncorrected**	**Corrected[1]**
Mammoth Red	56.2	65.8
Monriac	44.1	58.0
Meka Otofte	48.5	56.3
Krake	45.0	55.8
Monofix	36.5	45.9
Peroba	42.5	43.9
GW Monohybrid 149	33.9	34.6

LSD 0.05 = 7.1

[1] Based on a harvest of 34,750 beets per acre.
(111 rows with 313 beets per row and 208.7' row length, 22" row width and 8" spacing between beets.)

TABLE 4: BIOMASS FRESH WEIGHT YIELD

	Yield (tons/acre)		
Cultivar	**Root**	**Shoot***	**Total**
Mammoth Red	65.8	9.2	75.0
Monriac	58.0	11.9	69.9
Meka Otofte	56.3	15.9	72.2
Krake	55.8	19.6	75.4
Monofix	45.9	11.1	57.0
Peroba	43.9	11.7	55.6
GW Monohybrid 149	34.6	11.7	46.3

LSD 0.05 = 7.1

*Means were not statistically different at the 0.05 level.

TABLE 5: ROOT WATER CONTENT

Cultivar	% Water
Mammoth Red	91.2
Peroba	87.6
Monriac	86.0
Krake	85.1
Meka Otofte	84.9
Monofix	83.8
GW Monohybrid 149	78.8

LSD 0.05 = 4.73

TABLE 6: SHOOT WATER CONTENT

Cultivar	% Water
Monriac	91.1
Krake	89.6
Monofix	89.4
Mammoth Red	89.0
Peroba	89.0
Meka Otofte	88.5
GW Monohybrid 149	88.4

LSD 0.05 = 3.00

TABLE 7: BIOMASS DRY WEIGHT YIELD

	Yield (tons/acre)		
Cultivar	**Root**	**Shoot**	**Total**
Meka Otofte	8.5	1.7	10.2
Krake	8.4	2.1	10.4
Monriac	9.1	1.1	9.2
GW Monohybrid 149	7.3	1.3	8.6
Monofix	7.4	1.1	8.5
Mammoth Red	5.8	1.0	6.8
Peroba	5.4	1.3	6.7
LSD 0.05 =	1.01	1.53	

TABLE 8: BIOMASS APPORTIONMENT BETWEEN ROOT AND SHOOT

Cultivar	% of total biomass			
	Root		Shoot	
	Fresh	Dry	Fresh	Dry
GW Monohybrid 149	74.7	84.9	25.3	15.1
Krake	74.0	79.8	26.0	20.2
Mammoth Red	87.7	85.3	12.3	14.7
Meka Otofte	78.0	83.3	22.0	16.7
Monofix	87.1	82.3	19.5	12.9
Monriac	83.0	88.0	17.0	12.0
Peroba	79.0	80.6	21.0	19.4
Mean	79.6	83.5	20.4	15.9

TABLE 9: ROOT SUGAR AND POTENTIAL ALCOHOL YIELD

Cultivar	Sucrose (%)	Reducing Sugars (% Sucrose Equiv)	Total Fermentable Sugar (tons/acre)	Potential Alcohol (gal/acre)
Krake	11.52	0.15	6.46	928
Meka Otofte	10.75	0.62	6.40	910
Monriac	9.40	0.42	5.70	814
GW Monohybrid 149	14.99	0.15	5.24	743
Monofix	10.99	0.30	5.18	740
Peroba	7.96	0.55	3.74	534
Mammoth Red	5.44	0.19	3.70	528

LSD 0.05 = 0.60 LSD 0.05 = 87

TABLE 10: BIOMASS COMPOSITION AND APPORTIONMENT

		Composition (% dry weight)					
Cultivar	Biomass	Oils	Polyphenols	Ethanol Extractives	Crude Fiber	Lignin	Residual Biomass
Mammoth Red	Shoot	3.6	5.2	20.6	11.4	10.4	48.8
	Root	0.6	5.2	55.1	7.5	9.8	14.9
	Whole Plant	1.1	5.2	55.1	8.2	9.9	20.6
Krake	Shoot	4.0	4.9	15.1	11.8	16.9	46.9
	Root	1.7	4.4	66.2	5.9	6.7	15.1
	Whole Plant	2.2	4.5	56.0	7.1	8.7	21.5
Meka Otofte	Shoot	3.5	6.6	21.4	10.5	17.0	70.7
	Root	1.9	3.6	63.5	6.4	8.1	16.5
	Whole Plant	2.2	4.2	55.1	7.2	9.9	21.3
Monofix	Shoot	3.6	4.1	21.2	10.3	15.2	45.6
	Root	1.3	4.1	63.2	6.2	7.8	17.3
	Whole Plant	1.6	4.1	57.4	6.7	8.8	21.2
Monriac	Shoot	3.2	5.2	21.5	13.0	16.6	40.4
	Root	1.5	3.3	67.6	5.4	7.2	15.2
	Whole Plant	1.7	3.6	62.3	6.3	8.3	18.1
Peroba	Shoot	3.2	5.5	21.1	11.3	17.2	41.7
	Root	0.7	4.3	69.2	3.4	6.3	17.0
	Whole Plant	1.2	4.6	59.6	5.0	8.5	21.9
GW 149	Shoot	3.7	5.2	28.7	10.6	13.3	38.5
	Root	1.8	3.6	75.5	3.7	5.1	10.3
	Whole Plant	2.2	3.9	66.5	5.0	6.7	15.7
Mean for all Cultivars	Shoot	3.5	5.2	21.5	11.3	13.8	43.2
	Root	1.2	4.1	66.7	5.5	7.3	15.2
	Whole Plant	1.8	4.3	58.9	7.3	8.7	20.0

TABLE 11: YIELD OF EXTRACTIVES AND RESIDUAL BIOMASS

		Yield (lbs/acre)					
Cultivar	Biomass	Oils	Polyphenols	Ethanol Extractives	Crude Fiber	Lignin	Residual Biomass
GW 149	Shoot	129	181	999	369	463	1340
	Root	260	519	10,887	534	735	1435
	Whole Plant	389	700	11,886	903	1198	2825
Krake	Shoot	164	201	619	484	693	1923
	Root	280	725	10,910	972	1104	2488
	Whole Plant	444	926	11,529	1456	1797	4411
Mammoth Red	Shoot	81	118	466	258	235	1103
	Root	69	638	7,167	867	1133	1722
	Whole Plant	150	756	7,633	1125	1368	2825
Meka Otofte	Shoot	148	279	905	444	719	1722
	Root	323	611	10,782	1087	1375	2801
	Whole Plant	471	890	11,687	1531	2094	4523
Monofix	Shoot	85	97	500	243	359	1076
	Root	193	610	9,404	923	1161	2574
	Whole Plant	278	707	9,904	1166	1520	3650
Monriac	Shoot	70	113	469	283	362	881
	Root	223	491	10,059	804	1071	2262
	Whole Plant	293	604	10,528	1087	1433	3143
Peroba	Shoot	93	138	569	301	367	1149
	Root	76	465	7,487	368	682	1839
	Whole Plant	169	603	8,056	669	1049	2988
Mean for All Cultivars							
	Shoot	110	161	647	340	457	1313
	Root	203	580	9,528	794	1037	2167
	Whole Plant	313	741	10,175	1134	1494	3481

TABLE 12: ENERGY CONTENT OF BIOMASS, EXTRACTIVES, AND BIOMASS

	Energy (cal/gram)						
	Biomass* At Harvest		Extractives and Residue			Residual Biomass	
Cultivar	Shoot	Root	Oils	Polyphenols	Ethanol Extractives	Shoot	Root
GW 149	3461	3795	8627	4070	3748	3146	3765
Krake	3607	3727	8627	4338	3856	3350	3624
Mammoth Red	3613	3628	8920	4673	3964	3309	-
Meka Otofte	3676	3720	8879	4323	3937	3223	3668
Monofix	3644	3749	8747	4552	3934	3263	3684
Monriac	3674	3688	8955	3956	3839	3461	3536
Peroba	3601	3661	8566	4270	4085	3353	3459
Mean	3611	3710	8760	4312	3905	3301	3623

* Minimum of 5 replicates, all others 3-6 replicates

TABLE 13: BIOMASS ENERGY YIELD

Energy Yield ($x10^6$ kcal/acre)
() = Percent of Total

Cultivar	Shoot	Root	Total	Shoot/Root Ratio
Meka Otofte	6.0(17.2)	28.9(82.8)	35.2	0.21
Krake	5.9(17.3)	28.3(82.7)	34.3	0.21
Monriac	3.6(11.8)	26.8(88.2)	30.5	0.13
GW 149	4.0(13.6)	25.4(86.4)	29.6	0.16
Monofix	3.2(11.1)	25.5(88.9)	28.8	0.13
Mammoth Red	3.3(14.7)	19.1(85.3)	22.3	0.17
Peroba	4.0(18.3)	17.9(81.7)	21.8	0.22

LSD 0.05 = 1.6

TABLE 14: ENERGY YIELD AND APPORTIONMENT

Yield ($x10^6$Kcal/acre)
() = Percent of Total Energy

Cultivar	Extractives (Whole Plant)			Residue after Extraction		
	Oils	Polyphenols	Ethanol Extractives	Shoot	Root	Total
GW 149	1.52(4.9)	1.29(4.2)	20.21(65.6)	3.1(10.1)	4.70(15.2)	30.28
Krake	1.74(4.8)	1.82(5.1)	20.16(56.1)	4.71(13.1)	7.50(20.9)	35.93
Mammoth Red	0.61(2.5)	1.60(6.5)	13.72(56.1)	2.40(9.8)	6.12(25.0)	24.45
Meka Otofte	1.90(5.1)	1.75(4.7)	20.87(55.7)	4.22(11.3)	8.76(23.4)	37.50
Monifix	1.10(3.6)	1.46(4.8)	17.67(58.0)	2.48(8.1)	7.78(25.5)	30.49
Monriac	1.19(4.0)	1.08(3.6)	18.33(61.8)	1.40(8.1)	6.64(22.4)	29.64
Peroba	0.67(2.8)	1.17(4.9)	14.93(62.1)	2.76(11.5)	4.53(18.8)	24.06

TABLE 15: SUGAR CONTENT AND POTENTIAL ALCOHOL YIELD OF BEETS GROWN OUTSIDE MONTANA
(from Theurer et al 1981)

Cultivar	Trial	Sucrose %	Reducing Sugar %	Total Fermentable Sugars (tons/acre)	Potential Alcohol (gallons/acre)
GW D2	Logan	16.6	0.17	4.85	693
	Aberdeen	16.6	0.19	5.92	845
	National	-	-	-	635
	Intermountain	-	-	-	683
	Misc.	-	-	-	768
Mammoth Red	Misc.	-	-	-	610
Monriac	National	-	-	-	640
Meka Otofte	Logan	13.5	0.23	5.18	741
	Intermountain	-	-	-	716
Krake	Aberdeen	14.3	0.17	6.88	983
	Misc.	-	-	-	825
Monofix	Logan	13.7	0.15	4.81	686
Peroba	Misc.	-	-	-	776

TABLE 16: RAW SUGAR CONTENT FOR SUGAR BEETS, UNITED STATES 1970-78*

Year	Raw Sugar %
1970	12.9
1971	13.1
1972	12.8
1973	13.1
1974	13.2
1975	13.5
1976	13.3
1977	12.4
1978	12.8

* Calculated from data in: Walsh, P.A. 1980. Agricultural Statistics. 1980. USDA. US Government Printing Office, Washington, D.C.

TABLE 17: SUGAR CONTENT, YIELD AND POTENTIAL ALCOHOL FOR SELECTED CULTIVARS GROWN AT THE SOUTHERN RESEARCH CENTER, HUNTLEY, MT. *

Cultivar	Crop Year	Sugar %	Sugar Yield tons/acre	Potential Alcohol gallons/acre
HH30	1982	16.0	4.94	706
	1981	16.1	4.36	623
	1980	19.0	4.07	582
	1979	18.6	5.02	718
GW MonoHy D7	1982	16.0	4.67	667
	1981	16.5	4.12	589
	1980	19.9	3.92	561
	1979	18.8	5.18	740
GW 81 MSC 121	1982	15.6	4.51	644
	1981	-	-	-
	1980	-	-	-
	1979	-	-	-
GW MonoHy D2	1982	15.5	4.50	642
	1981	16.7	4.12	588
	1980	19.1	3.50	500
	1979	18.9	4.88	697
Beta KW834	1982	15.1	4.47	639
	1981	15.1	3.49	498
	1980	18.1	3.20	458
	1979	19.3	5.24	749

* Data from annual reports of the Southern Research Center, Huntley, Montana. Cultivars listed are the top 5 performers with respect to recoverable sugar. Sugar yields given were calculated from root fresh weight yields and sugar content. Because of conventional topping practices to remove leaf biomass and a portion of the root crown, the values for potential alcohol are conservative.

TABLE 18: 1978 YIELDS AND POTENTIAL ALCOHOL YIELDS OF MAJOR ENERGY CROPS (from Doney 1980)

Variety	Yield (1978)	Potential alcohol 90% conversion (gallons/unit)	Alcohol yield (gallons/acre)
Corn (bu/a)	101.2	2.8/bu	283
Wheat (bu/a)	31.6	2.6/bu	82
Potatoes (cwt/a)	263	1.2/cwt	316
Sugar beet (ton/a)	20.3	24.3/ton	493

TABLE 19: FUEL BEET PRODUCTION COST (from Doney 1980)

Expense	Cost per Gallon
Fuel beet production	$1.03
Sugar Conversion to alcohol	0.60
Credit for pulp + stillage	<0.25>
Adjusted Cost	**$1.38**

TABLE 20: SELECTED ENERGY VALUES

Material	Calorific Value (cal/g	Reference
Biomass		
Calotropis procera whole plant	4165	Erdman and Erdman 1981
Calotropis procera leaves	4099	Erdman and Erdman 1981
Wheat staw	4722	Baumeister 1966
Wood	5000	Baumeister 1966
Cereal gram[A] (barley, corn, wheat)	3500	Pimental et al 1981
Euphorbia esula shoot	4343	Wiatr 1984a
Euphorbia esula root	4214	Wiatr 1984a
Euphorbia esula leaves	4643-5192	Wiatr 1984b
Polypohenols		
Euphorbia esula	4123-6033	Wiatr 1984b
Natural oils		
Calotropis procera	10,003	Erdman and Erdman 1981
Euphorbia esula	9483-10,095	Wiatr 1984b
Sunflower	9431	Peterson et al 1981
Safflower	9445	Peterson et al 1981
Winter rape	9536	Peterson et al 1981
Biosynthetic oils		
PERC	8778	Elliot 1981
LBL	8074	Elliot 1981
Fossil-derived Fuels		
Anthracite coal	7156	Bolz and Tuve 1970
Lignite coal	3889	Bolz and Tuve 1970
Petroleum	10,506	8aumeister 1966
No. 2 Fuel oil	11,022	Elliot 1981
Diesel	10,818	Peterson et al 1981
Misc		
Ethanol	7091	West 1974
Sucrose	3939	West 1974
Glucose	3718	West 1974

[A] Calculated from yield and potential energy data

TABLE 21: MASS AND ENERGY YIELDS FOR SELECTED MONTANA CROPS

		Mass Yield (d.w. tons/acre)				Energy Yield[D] (x10^{6}Kcal/acre)			
Crop	**Year**	**Crop[A]**	**Fermentable[B] Carbohydrate**	**Residue[C]**		**Fermentable Carbohydrate**	**Residue**		**Total**
		Root		**Root Pulp**	**Leaves**		**Root Pulp**	**Leaves**	
Sugar beet HH30	1982	7.53	5.79	1.74	1.81	20.7(66.4)	4.6(14.7)	5.9(18.9)	31.6
GW MonoHy 07		7.53	5.47	1.65	1.71	19.5(65.9)	4.5(15.2)	5.6(18.9)	29.6
GW 81 MSC 121		7.05	5.28	1.76	1.69	18.9(64.7)	4.8(16.4)	5.5(18.8)	29.2
GW MonoHy 02		7.07	5.27	1.80	1.70	18.8(64.0)	5.0(17.0)	5.6(19.1)	29.4
Beta KW 834		7.22	5.24	1.97	1.73	18.7(62.3)	5.6(18.7)	5.7(19.0)	30.0
		Grain		**From Grain**	**Straw**		**From Grain**	**Straw**	
Barley	1977	0.88	0.59	0.29	2.11	2.1(17.8)	0.7	9.0	11.8
	1978	1.03	0.69	0.34	2.47	2.5(18.0)	0.8	10.6	13.9
	1979	0.94	0.63	0.31	2.26	3.4(25.2)	0.4	9.7	13.5
		Grain		**From Grain**	**Straw**		**From Grain**	**Straw**	
Wheat	1977	0.78	0.40	0.22	2.56	1.8(19.6)	0.7	6.7	9.2
	1978	0.91	0.58	0.25	1.82	2.1(19.6)	0.8	7.8	10.7
	1979	0.68	0.43	0.19	1.36	1.5(18.5)	0.7	5.9	8.1
		Grain		**From Grain**	**Stover**		**From Grain**	**Stover**	
Corn	1977	1.90	1.41	0.50	2.09	5.0(33.3)	1.0	9.0	15.0
	1978	2.02	1.49	0.53	2.22	5.3(33.3)	1.1	9.5	15.9
	1979	2.16	1.59	0.57	2.38	5.7(33.3)	1.2	10.2	17.1

[A] Crop Yields
Beet: Yield data given are for the top 5 performers in 1982 trials at the Southern Research Center at Huntley, MT. An additional 15% yield has been included for root crowns that would not be removed from fuel beets.
Dry weight yield = 21.2% fresh-weight yield.
Barley: 1 bu = 48 lb.
Wheat : 1 bu = 60 lb.
Corn: 1 bu = 56 lb.

[B] Fermentable carbohydrate (F.C.)
Beet: F.C. = Root fresh wt. yield x (% sucrose + 0.3% reducing sugar)
Barley: F.C. = 2.5% sugar + 64.6% starch (Anon 1980)
Wheat: F.C. = 63.8% starch (Anon 1980)
Corn: F.C. = 1.8% sugar + 72.0% starch (Anon 1980)

[C] Residue
Beet: Root pulp = Crop yield -- fermentable carbohydrate
Leaves = 24% of crop yield
Barley: Grain residue = Crop yield -- fermentable carbohydrate
Straw = 240% grain yield (from Robinson 1980)
Wheat: Grain residue = Crop yield -- fermentable carbohydrate
Straw = 200% grain yield (from Robinson 1980)
Corn: Grain residue = Crop yield -- fermentable carbohydrate
Stover = 110% of grain yield (from Robinson 1980)

[D] Energy Yield
The calorific value of sucrose (3939 cal/g) was used to calculate energy yield of fermentable carbohydrate for all crops.
Beet: Root pulp energy = Total root energy yield -- fermentable carbohydrate energy yield.
Root biomass energy = 3710 cal/g
Shoot biomass energy = 3611 cal/g
Barley, wheat, and corn:
Grain residue energy yield = Grain energy yield -- fermentable carbohydrates
Grain energy = 3500 cal/g
Residue straw or stover = 4722 cal/g (Pimental et al 1981)

TABLE 22: MASS AND ENERGY YIELDS FOR FUEL BEET CULTIVARS

	Mass Yield (d.w. tons/acre)				Energy Yield (10^6Kcal/acre)			
		Fermentable	Residue		Fermentable	Residue		
Cultivar	Crop	Carbohydrate	Root Pulp	Leaves	Carbohydrate	Root Pulp	Leaves	Total
Meka Otofte	8.5	6.40	2.1	1.7	22.9	5.8	6.0	34.7
Krake	8.3	6.46	1.8	2.1	23.1	5.0	5.9	34.0
Monofix	7.4	5.18	2.2	1.1	18.5	6.7	3.2	28.4
GW MonoHy 149	7.3	5.24	2.1	1.3	18.7	6.4	4.0	29.1
Monriac	8.1	5.70	2.4	1.1	20.4	6.7	3.6	30.8
Mammoth Red	5.8	3.70	2.1	1.0	13.2	5.9	3.3	22.4
Peroba	5.4	3.74	1.7	1.3	13.4	4.5	4.0	21.9
Mean of 5 Top Performing Sugar Beet cvs. at Huntley, MT (1982 Trials)	7.2	5.4	1.8	1.7	19.3	4.9	5.7	29.9

TABLE 23: ROOT SUCROSE CONTENT - DRY WEIGHT BASIS

Cultivar	Type	Percent Sucrose Fresh weight	 Dry weight
Krake	SxF	11.4	76.6
Meka Otofte	FxF	10.8	71.2
Monriac	SxF	9.4	67.1
GW Monohybrid 149	SxS	15.0	70.8
Monofix	SxF	11.0	67.8
Peroba	FxF	8.0	64.2
Mammoth Red	FxF	5.4	61.3

TABLE 24: FERMENTABLE CARBOHYDRATE AND POTENTIAL ALCOHOL YIELDS OF MONTANA CROPS

Crop	Year	Fermentable Carbohydrate[A] (d.w. tons/acre)	Potential Alcohol[B] (gallons/acre)
Barley	1977	0.59	84
	1978	0.69	99
	1979	0.63	90
Wheat	1977	0.50	71
	1978	0.58	83
	1979	0.43	61
Corn	1977	1.41	201
	1978	1.49	213
	1979	1.59	227

[A] See Table 21 for calculation of fermentable carbohydrate.

[B] 14 lbs. fermentable carbohydrate equals one gallon ethanol.

TABLE 25: RAW MATERIALS AND PRODUCTS FROM FODDER BEETS (modified from Kosaric et al 1983)

Material	Yield per acre
Raw Materials	
Roots[A]	10.1 tons dry matter
Tops[A]	6.8 tons dry matter
Sugar from roots	4.7 tons dry weight
After Processing[B]	
Yeast biomass	590 lbs. dry matter
Ethanol	2.1 tons = 638 gallons
Pulp[C]	2.3 tons dry matter

[A] Roots = 21.5% dry matter
Tops = 15.9% dry matter

[B] Processing by anaerobic fermentation of sugars using a yeast strain with a high conversion yield of ethanol (e.g. Saccharomyces diastaticus 62).

[C] Pulp = beet residue remaining after extraction of sugar and juice from roots.

LITERATURE CITED

Anon. 1980. Fuel from Farms. A Guide to Small Scale Ethanol Production. Technical Information Center. U.S. Dept. of Energy. Oak Ridge, Tennessee.

Bergen, P. 1962. An improved method for the evaluation and selection of sugar beets in relation to sugar content and type. J. Agric. Res. 40:867-915.

Buchanan, R.A., I.M. Cull, F.H. Otey and C.R. Russell 1978. Hydrocarbon and rubber producing crops: evaluation of U.S. plant species. Econ. Bot. 32:131-145.

Baumeister, T. (ed.) 1966. Standard handbook for mechanical engineers. 7th ed. McGraw-Hill, NY.

Doney, D.L. 1980. Sugarbeet-fodder beet as a source of alcohol fuel. Utah Agric. Exp. Sta. Journal paper No. 2571. Logan, Utah.

Doney, D.L. 1981A. Energy from field crops. Proceedings of the Great Plains Agricultural Council. MSU, Bozeman, MT.

Doney, D.L. and J.C. Theurer 1980. Alcohol Fuel from Sugarbeets. Utah Science 41:40-43.

Doney, D.L., R.E. Wyse and J. Clair Theurer 1981. The relationship between cell size, yield, and sucrose concentration of the sugarbeet root. Can. J. Plant Sci. 61:447-453.

Dotti, L.B. and J.M. Orten 1971. Laboratory Instructions in Biochemistry. 8th edition. C.V. Mosby Co., St. Louis, Missouri, pp. 106-107.

Erdman, M.D. and B.A. Erdman 1981. Calotropis procera as a source of plant hydrocarbons. Econ. Bot. 35(4):467-472.

Haby, V., R.A. Pence, R. Larson, G. Stallknecht 1981. Sugar Beet variety performance trials. Montana Agric. Expt. Sta. Report No. 654. Southern Research Center, Huntley, MT.

Hills, F.J., R. Albaugh and R. Pearl 1955. Value and use of sugarbeet tops. Agricultural Extension Service, University of California, Davis.

Holliday, R. 1966. Solar energy consumption in relation to crop yield. Agricultural Progress 41:24-34.

Horwitz, W. (ed.) 1980. Official methods of the Association of Official Analytical Chemists. 13th Edition. AOAC. Washington, D.C.

Illanes, A. and G. Schaffeld 1983. Protein enrichment of treated and untreated leached beet cosette. Biotechnol. Letters 5:305-310.

Kosaric, N., A. Wieczorek and S. Kliza 1983. Ethanol production from fodder beets. Biotechnol and Bioeng. 25:1737-1745.

Nathan, R.A. 1978. Fuels from sugar crops. DOE Critical Review Series. (Technical Information Center, U.S. Department of Energy).

Odlemeyer, R.K. 1975. Introgression hybridization as a breeding method in Beta vulgaris. J. Amer. Soc. Sugar Beet Technol. 18:269-273.

Odum, E.R. 1959. Fundmentals of Ecology. Saunders Press, Philadelphia, PA.

Pimental, D., M.A. Moran, S. Fast, G. Weber, R. Bukantis, L. Balliett, P. Boveng, C. Cleveland, S. Hindmann and M. Young 1981. Biomass energy from crop and forest residues. Science 212(5):1110-1115.

Powers, L. 1957. Identification of genetically superior individuals and the prediction of genetic gains in sugar beet breeding programs. J. Amer. Soc. Sugar Beet Technol. 9:408-432.

Robinson, J.S. (ed.) 1980. Fuels from Biomass: Technology and Feasibility. Noyes Data Corp. Park Ridge, NJ.

Surface, G.T. 1910. The story of sugar. D. Appleton and Co., New York, NY.

Theurer, J.C., D.L. Doney and J. Gallian 1981. Fodder beet: potential alcohol fuel crop. Utah Science 42(2):63-67.

Ware, L.S. 1880. The sugar beet. Henry Corey Baird & Co. Philadelphia, PA.

Weast, R.C. (ed.) 1973. CRC Handbook of Chemistry and Physics. CRC Press, Cleveland, OH.

Wiatr, S.M. 1984. Effect of drying on yield and calorific values of extractables from Leafy Spurge (Euphorbia esula). Biotechnol. and Bioeng. 26:335-339.

Wiatr, S.M. 1984. The biomass potential of Leafy Spurge (Euphorbia esula L.). Final Report. Renewable Energy Division, Montana Dept. of Natural Resources and Conservation, Helena, MT.

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